CLAIMS

We claim:

1. A cantilever for use in a tapping-mode atomic force microscope, the cantilever comprising:

a cantilever arm having a fixed end and a free end, the cantilever arm having a fundamental resonance frequency and at least one higher order resonance frequency; and

a probe tip projecting from the cantilever arm near the free end,

wherein the cantilever arm has a shape selected to tune the fundamental resonance frequency of the fundamental mode or a resonance frequency of a selected higher order mode so that the resonance frequency of the selected higher order mode and the fundamental resonance frequency has an integer ratio.

2. The cantilever of claim 1, wherein the integer ratio comprises whole numbers and fractional numbers slightly greater than or less than the nearest whole numbers so that when the cantilever is driven at a driving frequency at or slightly below or slightly above the fundamental resonance frequency, the resonance frequency of the selected higher order mode is an integer multiple of the driving frequency.

3. The cantilever of claim 2, wherein the integer ratio comprises whole numbers and fractional numbers within 2.0% of the nearest whole numbers.

4. The cantilever of claim 1, wherein the free end of the cantilever arm has a second shape selected to tune the fundamental resonance frequency of the cantilever to a value that

is integer divisible of the resonance frequency of the selected higher order mode.

5. The cantilever of claim 4, wherein the second shape comprises tapered sides forming the free end of the cantilever arm.

6. The cantilever of claim 1, wherein the cantilever arm comprises a first geometric feature disposed at a predefined location of the cantilever arm, the first geometric feature operating to modify the mass of the cantilever arm at the predefined location to tune the fundamental resonance frequency or the resonance frequency of the selected higher order mode of the cantilever so that the fundamental resonance frequency and the resonance frequency of the selected higher order mode has an integer ratio.

7. The cantilever of claim 6, wherein the first geometric feature operates to reduce the effective width of the cantilever arm at the predefined location.

8. The cantilever of claim 6, wherein the first geometric feature operates to increase the effective width of the cantilever arm at the predefined location.

9. The cantilever of claim 6, wherein the first geometric feature operates to reduce the thickness of the cantilever arm at the predefined location.

10. The cantilever of claim 6, wherein the first geometric feature operates to increase the thickness of the cantilever arm at the predefined location.

11. The cantilever of claim 6, wherein the first geometric feature is located at a location of high mechanical bending stress for the fundamental mode or the selected higher order mode.

12. The cantilever of claim 11, wherein the first geometric feature is located at a high curvature region of the fundamental mode or the selected higher order mode.

13. The cantilever of claim 11, wherein the first geometric feature is located at a high displacement region of the fundamental mode or the selected higher order mode.

14. The cantilever of claim 11, wherein the first geometric feature operates to alter the effective spring constant of the cantilever arm.

15. The cantilever of claim 11, wherein the first geometric feature comprises a mass removal region.

16. The cantilever of claim 15, wherein the first geometric feature operates to remove mass from a high curved region of the fundamental mode or the selected higher order mode to decrease the resonance frequency of the fundamental mode or the selected higher order mode.

17. The cantilever of claim 15, wherein the first geometric feature operates to remove mass from a high displacement region of the fundamental mode or the selected higher order mode to increase the fundamental resonance frequency or the resonance frequency of the selected higher order mode.

18. The cantilever of claim 15, wherein the mass removal region comprises a first notch and a second notch formed at a first side and an opposite second side, respectively, of the cantilever arm.

19. The cantilever of claim 15, wherein the mass removal region comprises an opening formed in the body of the cantilever arm.

20. The cantilever of claim 19, wherein the mass removal region comprises a rectangular opening or a round opening.

21. The cantilever of claim 19, wherein the selected mode is the third flexural mode of the cantilever and the mass removal region is positioned at a high curvature region of the third flexural mode.

22. The cantilever of claim 21, wherein the mass removal region is positioned at one-third of the total length away from the free end of the cantilever arm.

23. The cantilever of claim 11, wherein the first geometric feature comprises a mass addition region.

24. The cantilever of claim 23, wherein the mass addition region increases the effective width of the cantilever at the predefined location.

25. The cantilever of claim 23, wherein the mass addition region increases the thickness of the cantilever at the predefined location.

26. The cantilever of claim 23, wherein the first geometric feature operates to add mass to a high curved region of the

fundamental mode or the selected higher order mode to increase the resonance frequency of the fundamental mode or the selected higher order mode.

27. The cantilever of claim 23, wherein the first geometric feature operates to add mass to a high displacement region of the fundamental mode or the selected higher order mode to decrease the fundamental resonance frequency or the resonance frequency of the selected higher order mode.

28. The cantilever of claim 1, wherein the cantilever arm comprises a material selected from the group of silicon and silicon nitride.

29. The cantilever of claim 1, wherein the probe tip is coated with a material selected from the group of diamond coating material and diamond-like carbon coating material.

30. The cantilever of claim 11, wherein the cantilever arm comprises a rectangular shaped cantilever including the first geometric feature modifying the shape and the mass of the cantilever arm.

31. The cantilever of claim 11, wherein the cantilever arm comprises a V-shaped cantilever including the first geometric feature modifying the shape and the mass of the cantilever arm.

32. The cantilever of claim 1, wherein the cantilever arm further comprises a first electrode of an electrostatic actuator where a second electrode of the electrostatic actuator is formed outside the cantilever, the electrostatic actuator operating to alter the effective spring constant of the cantilever by applying an electric field between the first and second electrodes.

33. A method of operating a tapping-mode atomic force microscope for detecting material properties on the surface of a sample, the method comprising:

providing a cantilever having a cantilever arm and a probe tip formed on a free end of the cantilever arm, the cantilever arm having a shape selected to tune the fundamental resonance frequency of the fundamental mode or a resonance frequency of a selected higher order mode so that the resonance frequency of the selected higher order mode and the fundamental resonance frequency has an integer ratio;

vibrating the cantilever at or near the fundamental resonance frequency with a predetermined oscillation amplitude;

bringing the cantilever to the vicinity of the sample;

tapping the surface of the sample repeatedly using the probe tip; and

detecting changes in the amplitude or the phase at the frequency of a higher harmonic corresponding to the selected higher order mode as the cantilever is deflected in response to features on the surface of the sample.

34. The method of claim 33, wherein the resonance frequency of the selected higher order mode and the fundamental resonance frequency has an integer ratio or a ratio slightly below or slightly above an integer ratio.

35. The method of claim 33, further comprising:

moving the cantilever arm in a direction parallel to the surface of the sample with the tip repeatedly tapping the surface of the sample, wherein the direction comprises a

direction along the length of the cantilever arm and a direction along the width of the cantilever arm.

36. The method of claim 33, wherein providing a cantilever having a cantilever arm and a probe tip, the cantilever arm having a shape comprises:

providing a cantilever including a first geometric feature disposed at a predefined location of the cantilever arm, the first geometric feature operating to modify the mass of the cantilever arm at the predefined location to tune the fundamental resonance frequency or the resonance frequency of the selected higher order mode of the cantilever so that the resonance frequency of the selected higher order mode of the cantilever is an integer multiple of the fundamental resonance frequency of the cantilever.

37. The method of claim 36, wherein providing a cantilever including a first geometric feature disposed at a predefined location comprises:

providing a cantilever including a mass removal region as the first geometric feature, the mass removal region being located at a point of high mechanical bending stress for the fundamental mode or the selected higher order mode.

38. The method of claim 36, wherein providing a cantilever including a first geometric feature disposed at a predefined location comprises:

providing a cantilever including a mass removal region as the first geometric feature, the mass removal region being located at a point of high displacement for the fundamental mode or the selected higher order mode.

39. The method of claim 37, wherein providing a cantilever including a mass removal region as the geometric feature comprises:

providing a cantilever including an opening formed in the body of the cantilever arm at the predefined location.

40. The method of claim 36, wherein providing a cantilever including a first geometric feature disposed at a predefined location comprises:

providing a cantilever including a mass addition region as the first geometric feature, the mass addition region being located at a point of high mechanical bending stress for the selected higher order mode.

41. The method of claim 36, wherein providing a cantilever including a first geometric feature disposed at a predefined location comprises:

providing a cantilever including a mass addition region as the first geometric feature, the mass addition region being located at a point of high displacement for the fundamental mode or the selected higher order mode.

42. The method of claim 40, wherein providing a cantilever including a mass addition region as the first geometric feature comprises:

providing a cantilever where the mass addition region increases the effective width of the cantilever arm at the predefined location.

43. The method of claim 40, wherein providing a cantilever including a mass addition region as the first geometric feature comprises:

providing a cantilever where the mass addition region increases the thickness of the cantilever arm at a certain region.

44. The method of claim 33, wherein detecting changes in the amplitude or the phase at the frequency of a higher harmonic corresponding to the selected higher order mode comprises:

detecting changes in the phase at the frequency of the higher harmonic corresponding to the selected higher order mode by comparison with a reference signal phase-matched to the cantilever vibration at the driving frequency.

45. The method of claim 33, further comprising:

varying a driving voltage of the cantilever in response to changes in the amplitude or the phase of the frequency of the selected higher order mode to maintain the oscillation amplitude or the phase of the oscillation of the cantilever at a constant value.

46. The method of claim 33, further comprising:

varying a set-point amplitude of the cantilever defining the tip-sample equilibrium separation of the cantilever in response to changes in the amplitude or the phase of the frequency of the selected higher order mode to maintain the oscillation amplitude or the phase of the oscillation of the cantilever at a constant value.

47. A cantilever for use in a tapping-mode atomic force microscope, the cantilever comprising:

a cantilever arm having a fixed end and a free end; and

a probe tip projecting from the cantilever arm, the probe tip being positioned at a location of minimum

displacement of a selected mode of the cantilever for suppressing the harmonics generated by the selected mode.

48. The cantilever of claim 47, wherein the probe tip is located at a location where the selected mode has a node.

49. The cantilever of claim 47, wherein the cantilever arm includes a first geometric feature disposed at a predefined location of the cantilever arm, wherein the cantilever has a fundamental resonance frequency and at least one higher order resonance frequency, the first geometric feature is positioned at a location on the cantilever arm so that a resonance frequency of a selected higher order mode, different than the selected mode, of the cantilever is tuned to an integer multiple of the fundamental resonance frequency of the cantilever.

50. A method of detecting tip-sample engagement in a tapping-mode atomic force microscope, the method comprising:

providing a cantilever having a cantilever arm and a probe tip formed on a free end of the cantilever arm;

vibrating the cantilever at or near the fundamental resonance frequency with a predetermined oscillation amplitude;

bringing the cantilever to the vicinity of the sample;

measuring the amplitude of the cantilever vibrations at a selected higher order harmonic of the fundamental resonance frequency; and

detecting an increase in the amplitude of the cantilever vibrations at the selected higher order harmonic to indicate that the probe tip of the cantilever has engaged the sample surface.

51. The method of claim 50, wherein providing a cantilever having a cantilever arm and a probe tip formed on a free end of the cantilever arm comprises:

providing the cantilever arm having a shape selected to tune the fundamental resonance frequency of the fundamental mode or a resonance frequency of a selected higher order mode so that the resonance frequency of the selected higher order mode and the fundamental resonance frequency has an integer ratio.